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PARAMETERS DESIGN OF A PHASE SHIFT FULL BRIDGE CONVERTER WITH A RESONANT TANK FOR HIGH DIRECT CURRENT APPLICATIONS

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ABSTRACT

In high current power supply applications, phase shift full bridge zero voltage switching (PSFB ZVS) converters have been used with the benefit of ZVS technique. In a conventional PSFB converter, switching loss, conduction loss, and voltage drop on diodes of secondary side rectifier are experienced, and still left problems unsolved, especially with respect to high primary current. This paper presents parameters design of the PSFB with an additional resonant tank for high direct current applications considering all the problems mentioned above. Magnetizing inductance of transformer is determined. A series capacitor is added to reduce the high circulating current and current stress in the transformer. Both of these components are dealt as a resonant tank. Based on the characteristics of the resonant tank, ZVS area can be found. The voltage drop on diodes of secondary side rectifier can be stayed under limits, and conduction loss can be reduced if the capacitor and inductor are suitably parameterized. The parameters of transformer, resonant tank, and output filter are designed by proposed parameters design procedure. Simulation result demonstrates the switching loss, and conduction loss reduction by selecting the suitable values of magnetizing inductance, and resonant tank parameters. The performance of high current power supply is verified by the hardware experiment of a 500 A PSFB converter.

***KEYWORDS:** Conduction Loss, Voltage Drop, High Current Low Voltage, PSFB & Switching Loss*

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Original Article

1. INTRODUCTION

Phase shift full bridge zero voltage switching (PSFB ZVS) converters are extensively used in high current applications such as superconductivity, and electroplating which require high output current, small ripple, low conduction, and switching loss. In order to reduce the conduction loss, several topologies were proposed [1-5]. Among these topologies, the addition of a capacitor is a simple method [6]. However additional capacitor may cause the high voltage drop on diodes of secondary side rectifier. On the other hand, magnetizing inductance of transformer strongly affects the switching loss. If a higher inductance is applied, lower switching loss is obtained. However, too high magnetizing inductance also makes high voltage drop in rectifier diode [7]. The output current ripple is reduced double time if the Center-Tapped transformer is used as compared with double current topology [8]. The problems include switching loss, conduction loss, and voltage drop need to be minimized. In this paper, the PSFB converter with an additional capacitor, and series Center-Tapped transformers topology is used for high direct current applications. The parameters of converter are analyzed, and optimally designed for not only reducing the conduction loss, and switching loss but also maintaining the voltage drop on diodes of secondary side rectifier under limits. In case of constant output current, small value of magnetizing inductance makes high input current. But too high magnetizing inductance makes high voltage drop in rectifier diodes. The optimal value of magnetizing inductance is selected based on simulation result. The resonant tank of the converter is composed of

magnetizing inductance, leakage inductance of transformer, and additional capacitor. Characteristic of the resonant tank circuit is analyzed for the ZVS area, low voltage drop in rectifier diode, and also reducing the conduction loss. Circulating current can be reduced by suitably selecting the resonant frequency which leads to conduction loss reduction. The parameter of transformer, resonant tank, and output filter are designed following the proposed parameters design procedure. The simulation results demonstrated that the mentioned problems were overcome. Efficiency is increased by the suitable value of resonant tank parameters. The performance of high current power supply was verified by the hardware experiment of a 500 A PSFB converter. The circulating current reduction was compared in the cases with, and without the resonant tank. Based on the analysis, and design method studied in this paper, the PSFB with Center-Tapped transformers, and an additional capacitor topology can be applied for all of high current low voltage applications to achieve better performances of the power converter with switching and conduction loss reduction, and low output ripple as well.

2. PSFB CONVERTER ANALYSIS, AND DESIGN CONSIDERATIONS

Figure 1 shows the topology of a high current low voltage converter in which a PSFB converter with resonant tank and two series transformers are used. Resonant circuit includes an additional resonant capacitor C_r, resonant inductor L_r, and two magnetizing inductances $L_{m'}$. Center-Tapped topology operates at double switching frequency. This makes the current ripple lower, and reduces the size of output filter.

2.1 Magnetizing Inductance Analysis

Figure 2 shows the model of Center-Tapped transformer, and equations 1, 2, and 3 are the basic equations of transformer. Because the magnetizing current $i_{Lm}(t)$ does not contribute to the load current, but flows between the two bridge legs, the magnetizing current should be minimized. This deal can be carried out by increasing value of the magnetizing inductance. From the basic equations, in the case of constant output current of transformer I_{out}, if $L_{m'}$ increases, the magnetizing current are smaller, and small primary current is also smaller. Too high value of magnetizing inductance leads to high voltage drop on diodes of secondary side rectifier.

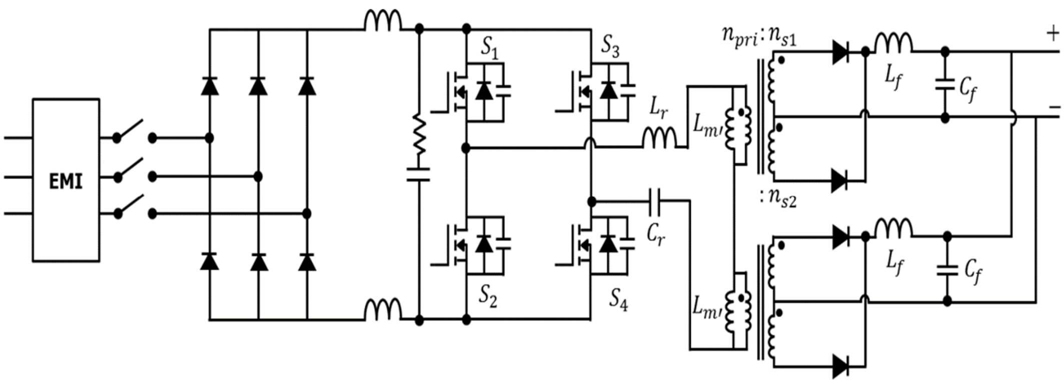

Figure 1: Circuit Diagram of the High Current Low Voltage Converter

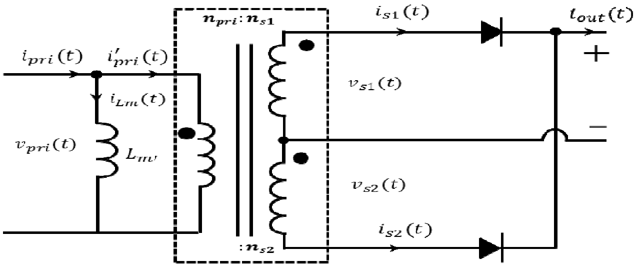

Figure 2: Model of Center-Tapped Transformer

$$i_{pri}(t) = i'_{pri}(t) + i_{Lm}(t)\,, \tag{1}$$

$$i_{Lm}(t) = \frac{1}{L_m}\int v_{pri}(t) \tag{2}$$

$$I_{out} = \frac{2}{T_s} n \int_{t=0}^{t=T_s} (i_{pri}(t) - i_{Lm}(t))dt \tag{3}$$

where n is the turn ratio of transformer, $i_{Lm}(t)$ is the magnetizing current, ipri(t) is the primary current, and $i'_{pri}(t)$ is the current which contributes to the load current, T_s is the switching period time, $I_{out}(t)$ is the average output current of transformer, vpri(t) is the primary voltage of transformer.

A benefit of reducing the magnetizing inductance $L_{m'}$ is the extension of soft switching toward smaller load currents, and a corresponding increase in the light-load efficiency. But small magnetizing inductance causes high input current, and plays significant role in switching loss increasing, particularly in high current converter, so the magnetizing inductance needs to be selected with a suitable value.

2.2 Resonant Tank Analysis

The term active power denotes the power that is really transferred to output, meanwhile, the term reactive power expresses the circulating power that is not transmitted to secondary side, and only circulates within the primary side. Additional capacitor helps reduce the reactive power which leads to attenuate the conduction loss. Indeed, the key waveform of the primary current of PSFB is shown in Figure 3. The primary current decreases rapidly during freewheeling period by using the additional capacitor.

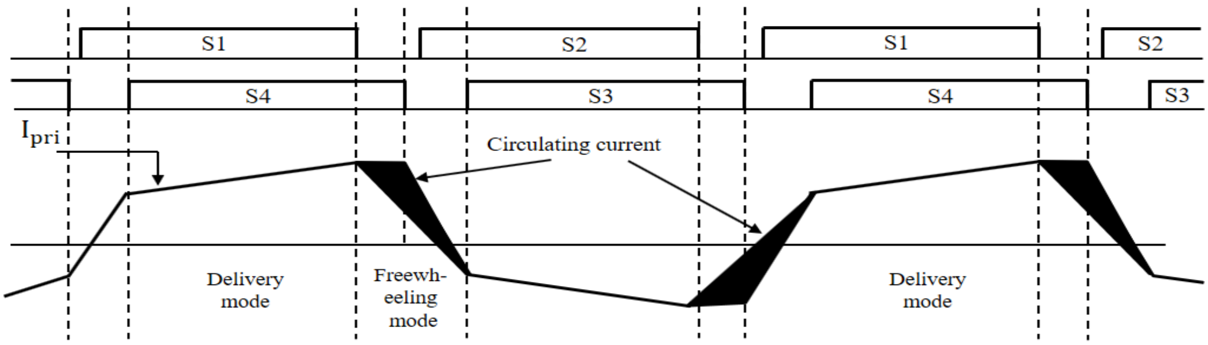

Figure 3: Key Waveform of the Primary Current in PSFB

Figure 4 shows the AC equivalent circuit of the PSFB which includes the equivalent load resistance R_{ac}, the input voltage V_i, the primary voltage Vpri, the resonant capacitor C_r, the resonant inductor L_r, and the magnetizing inductance L_m that equals the total magnetizing inductance of transformers, $L_m = 2L_{m'}$. The equivalent load resistance is $R_{ac} = \frac{8n^2}{\pi}R_o$, where R_o is the output load, n is the turn ratio of transformer

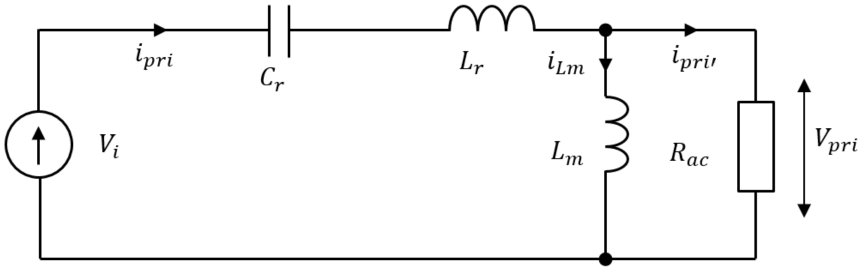

Figure 4: AC Equivalent Circuit

The voltage gain, M, is obtained as:

$$M = \frac{V_{pri}}{V_i/2} = \left| \frac{\left(\frac{f_s}{f_r}\right)^2 (m-1)}{\frac{f_s^2}{f_r^2} - 1 + j\frac{f_s}{f_r}\cdot\left(\left(\frac{f_s}{f_r}\right)^2 - 1\right).Q_m} \right|, \tag{4}$$

the parameters are defined:

$$m = \frac{L_m + L_r}{L_r},\ Q_m = \frac{1}{R_{ac}}\sqrt{\frac{L_r}{C_r}},\ f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{5}$$

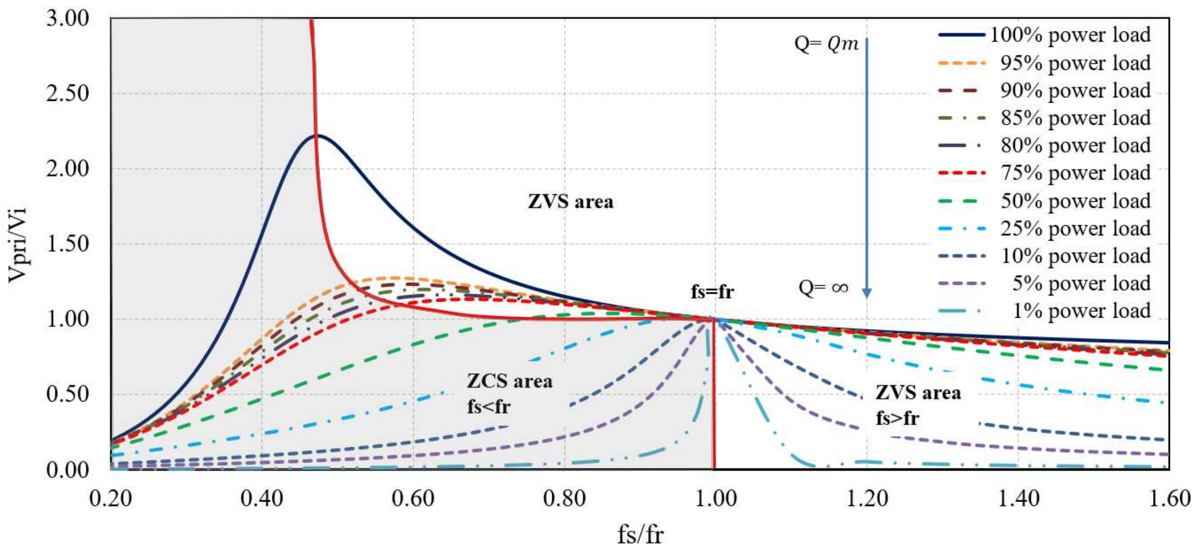

Figure 5: Characteristic of Resonant Circuit

Characteristics of resonant circuit strongly depend on the L_m, the quality factor Q_m, and the resonant frequency f_r. In Figure 5, the ZVS range is determined in the area in which the resonant frequency f_r is less than the switching frequency f_s ($f_s > f_r$). The voltage gain M can be increased by decreasing value of f_r which results in reducing the drop voltage in rectifier diode. The resonant frequency is adjusted to maintain the voltage drop in rectifier diode under the limits. Q_m Represents the changing rate of output load with respect to frequency. In PSFB, it was selected with small value so that the changing rate is small. However the function of resonant tank is lost in the case of too small Q_m. The Q_m value of the PSFB was selected from 0.2 to 1. The components of resonant tank are calculated by considering proper values of Q_m, and f_r.

3. PARAMETERS DESIGN OF THE PSFB CONVERTER

Figure 6 shows the proposed design procedure. According to above analyses, the major steps of the proposed design procedure are as follows:

Step 1: The turn ratio of transformers n is defined based on values of the output voltage regulation with minimum input voltage, effective phase shift ph_e [9]. The n can be obtained from equation 6:

$$\frac{V_o}{V_i/m} = n.ph_e\text{-}I_o.n^2.\frac{L_k}{V_i/m}.f_s \tag{6}$$

where m is the number of series transformers, L_k is the assumed leakage inductance, V_o is the output voltage.

Step 2: The output current ripple has the double switching frequency. Output inductance, and capacitor of each transformer can be obtained:

$$L_f = \frac{V_o(1\text{-}ph_e)}{2.f_s.\Delta I} \tag{7}$$

$$C_f = \frac{1}{L_f(2\pi f_f)^2} \tag{8}$$

where ΔI is the output current ripple, f_f is the cut-off frequency of output filter,

Step 3: Value of L_m is selected based on the simulation results, and consideration of primary current, and voltage drop in rectifier diode.

Step 4: As aforementioned, the Q_m value of the PSFB was selected from 0.2 to 1.0.

Step 5: In this step, the resonant frequency needs to be selected to ensure the ZVS condition~~s~~, the ciculating current reduction, and maintaining the voltage drop of output rectifier diode under the limits. As analysed in Section 2, the suitable resonant frequency is in the range of less than the switching frequency, proper value of f_r is selected based on

simulation results.

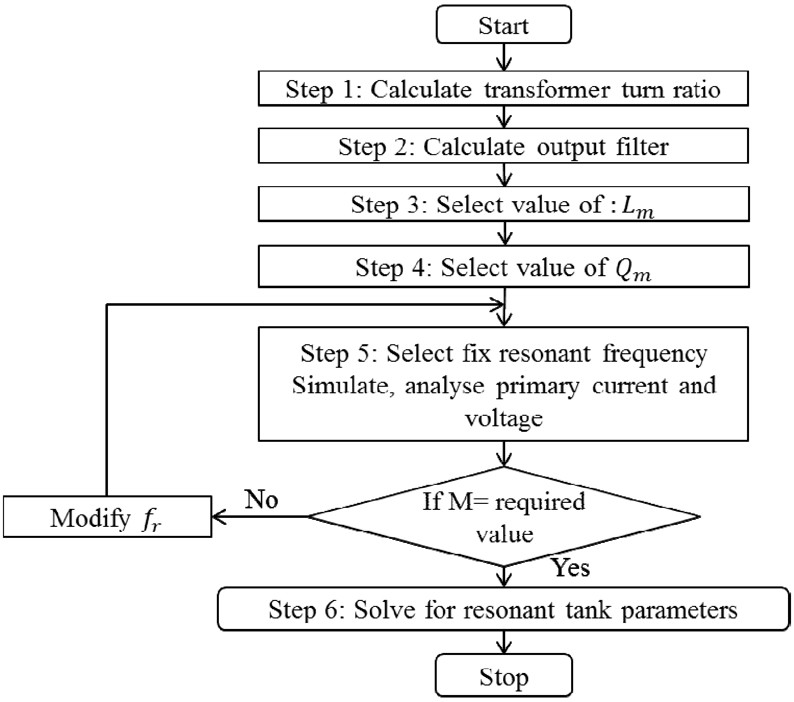

Figure 6: PSFB Parameters Design Procedure

Step 6: After simulation, and considering all the problems of the PSFB, if the simulation results have good performance. The resonant tank parameters are obtained in the following equations:

$$L_r = \frac{1}{2\pi . f_r} . R_{ac} . Q_m \tag{9}$$

$$C_r = \frac{1}{2\pi . f_r} . \frac{1}{R_{ac} . Q_m} \tag{10}$$

4. SIMULATION, AND THE EXPERIMENT RESULTS

4.1 Simulation Results

Table 1 shows the main parameters of 500 A power supply. Based on the flow chart in Section 3, the simulation result was obtained, and the design results of PSFB are shown in Table 2.

Table 1: Parameters of the High Current Power Supply

Items	Symbol	Value	Units
Input voltage	V_i	510	V_{DC}
Output current	I_0	500	A
Output voltage	V_0	10	V_{DC}
Switching frequency	f_s	18.75	kHz
Number of transformer	m	2	ea

Table 2: Parameters Design of the PSFB

Items	Symbol	Value	Units
Magnetizing inductance	L_m	150	µH
Resonant frequency	f_r	18	kHz
Resonant capacitor	C_r	2	µF
Resonant inductor	L_r	37.75	µH
Output inductor filter	L_f	240	µH
Output capacitor filter	C_f	150	µF

Figure 7 and Figure 8 show that the primary current, and current through IGBT depend non-linearly on the magnetizing inductance. A small value of L_m (less than 60 uH) leads the high primary current, and high current through IGBT. Eventually the switching loss is increased. The primary current waveform is almost the same with the low peak value when L_m is over 100 uH. On the other hand, voltage drop on diodes of secondary side rectifier is increased in the case of high magnetizing inductance as shown in Figure 9. Based on this analyis, optimal selection of L_m is 150 uH. Figure 10 shows the advantage of additional C_r. High value of the f_r helps reduce the circulating current during freewheeling mode. This magnitude significantly depends on f_r. In other constraints, f_r needs to be less than the switching frequency f_s mentioned in Section 2. Suitable value of f_r is 18 kHz.

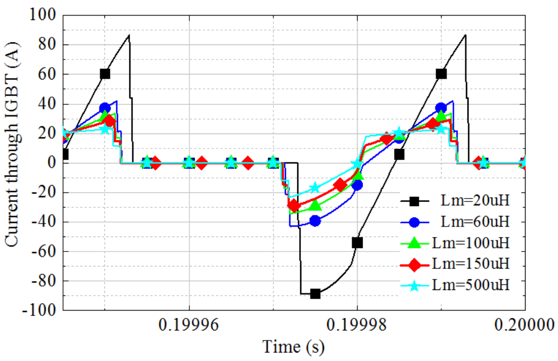

Figure 7: IGBT Current with Different value of L_m

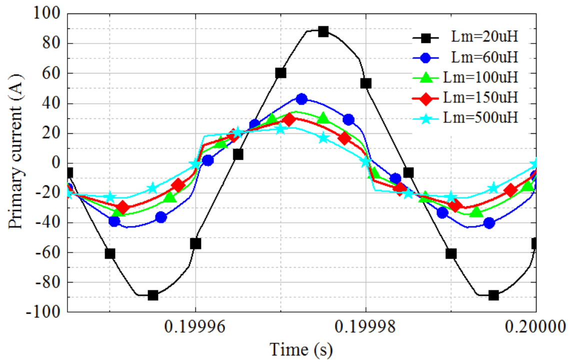

Figure 8: Primary Current with Different value of L_m

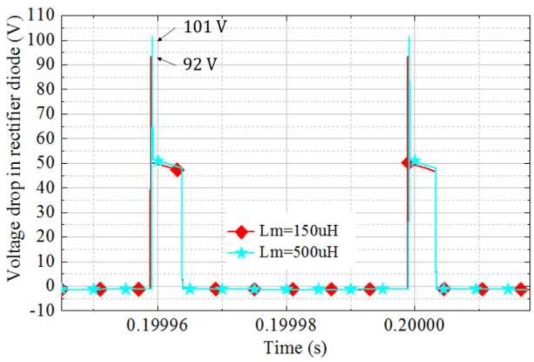

Figure 9: Voltage Ringing in Output Diode Rectifier

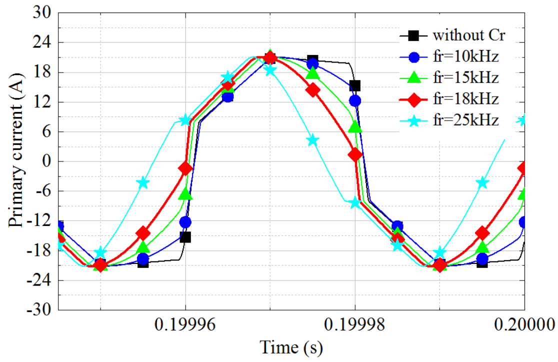

Figure 10: Primary Current with Different value of f_r

4.2 Experiment Results

Based on the design parameters, and results obtained from previous section, the main power devices for 500 A power supply were selected as Table 3. The experiment environment was implemented as shown in Figure 11.

Table 3: Main Power Devices of 500A Power Supply

Main devices	Manufacture	Part Numbers	Main Attributes
Primary IGBTs	SEMIKRON	SKM100GB12T4	V_{CES} = 1,200 V, I_C = 100 A, $r_{CE,on}$ = 10 mΩ
Secondary diodes	IXYS	DSA300I100NA	V_{RRM} = 100 V, I_{FAV} = 300 A, r_F = 1.09 mΩ
Input capacitor	United Chemi-Con	E36D551CPN332	Aluminum, 550 V, C= 3300 μF
Output Inductor	Core Electric		L= 220 μH
Output capacitor	EPCOS TDK	B32526T1336K	Film, 100 VDC, C= 33 μF
Resonant capacitor	Illinois	105PMB850KSP2	Film, 450 VAC, C= 1 μF
Transformer	Core Electric		n_{pri} = 12, n_{s1} = 1, n_{s2} = 1, P_{max} = 6.25 kW

Figure 12 shows the advantage of using resonant capacitor for reducing the circulating current. The RMS value of primary current reduces from 17.14 A to 15.8 A, the power loss reduces 150 W. This result is the same with the simulation result. On the other hand, the additional capacitor helps reduce the stress current to transformer, and remove the noise from transformer during operating. Output current was controlled at 500 A as shown in Figure 13. The voltage drop of rectifier diode in experiment result was considered. In the case of without capacitor the voltage drop equals 62 V. When the resonant capacitor is added, this value is increased to 80 V. The proposed design method is maintained under the limit of 100 V.

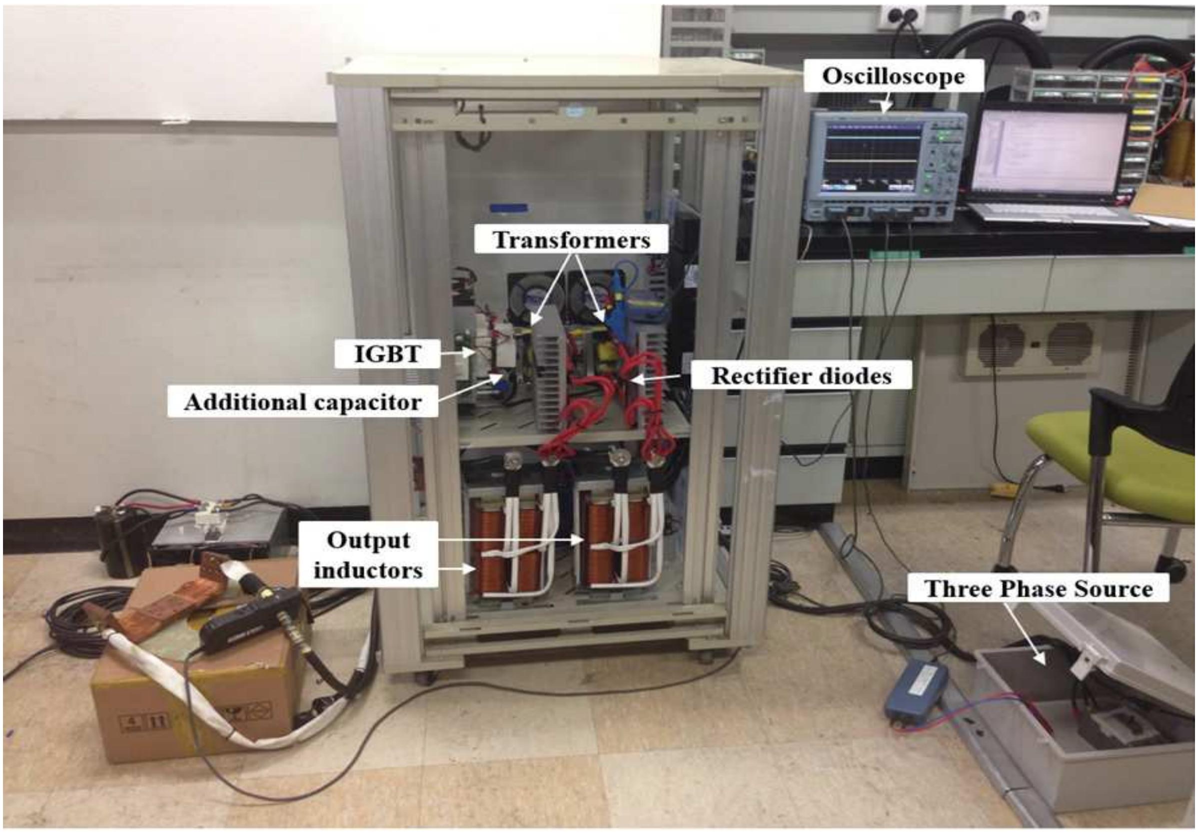

Figure 11: Fabrication of High Current Power Supply

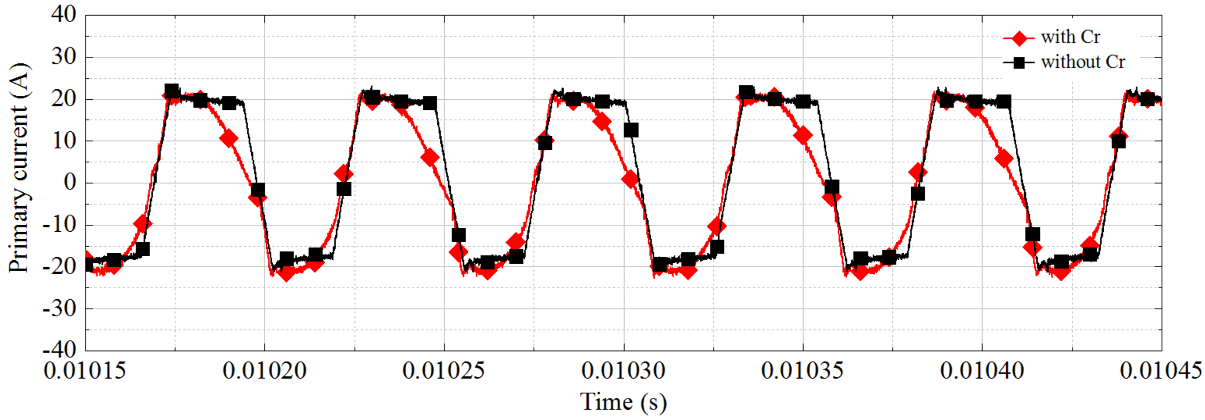

Figure 12: The primary Current in the Cases With, and Without Cr

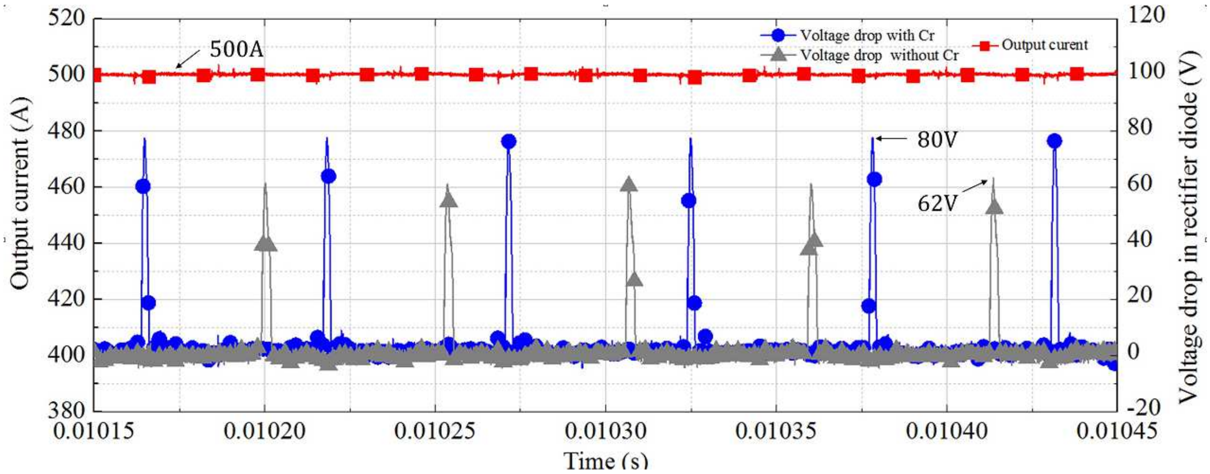

Figure 13: Output Current, and Voltage Drop in Rectifier Diode

5. CONCLUSIONS

In this paper, the authors presented a parameter design method of PSFB with resonant tank for high current applications. All the problems of the converter, switching loss, conduction loss, and voltage drop in rectifier diode were analyzed. The simple solution was applied by utilizing the benefits of additional capacitor, and optimal selection of magnetizing inductance, and resonant circuit. The switching loss was reduced by magnetizing inductance manipulation. The circulating current reduction was achieved, and the voltage drop on diode of secondary side rectifier could be limited by selecting suitable value of resonant frequency. The above mentioned simulation results were confirmed through a hardware implementation of 500 A power supply. As the result, the voltage drop was maintained under limits, and the total losses of the PSFB converter were reduced. Proposed method can be applied to high current applications.

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